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13. ABSTRACT *(Maximum 200 words)*

Experimental developments are reported that demonstrate the feasibility of using miniature optical stress sensors to determine the target response in 2-D loading situations arising due to projectile impacts. Oriented ruby chips embedded in aluminum and marble targets, at locations directly underneath rod impactors, were used to obtain time-resolved, in-situ measurements. Time resolution (~100 ns) and durations (~6 μs) reported here are intended to be representative and can be varied depending on the experimental requirements. Given the importance of obtaining in-situ, stress histories in targets subjected to 2-D dynamic loading, future work needs to address the development of analytic procedures to permit accurate and efficient inversion of the sensor output.

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I. INTRODUCTION AND OBJECTIVES

A prototype Army application involves the impact of a high velocity projectile on a target or an armor material; a detailed understanding of the projectile-target interaction including penetration is a problem of long standing and continuing interest.[1] With rapid advances in computational methods and capabilities, increasingly sophisticated material models are being used to examine and model high velocity impact phenomena.[2] Typical experimental measurements used to examine details of the projectile-target interaction and/or determine the validity of the numerical calculations consist of flash X-ray data and post-impact examination of the projectile and target response. These measurements, though valuable, are limited in scope in detailing the time evolution of the target and projectile material response for the time and length scales of interest. As such, in-situ stress sensors mounted at target locations underneath and in the vicinity of the impact region are expected to be quite valuable in quantifying the target response.

Although the need for in-situ sensors in targets is well recognized, there are both conceptual and practical difficulties in obtaining the needed data. The region underneath the impactor is subjected very rapidly to high stresses (tens to a few hundred kbar), large deformations, and complex loading conditions. The combination of extreme loading and short time scales (0.1 to tens of μs) makes it difficult to probe the target material accurately in regions of interest. Since high stresses and short durations are also encountered in plate impact experiments, there have been attempts to utilize diagnostics used in plane wave loading for the non-planar and 2-D (or 3-D) loading conditions typically encountered in projectile impact or explosive loading. There are several difficulties with this approach: obtaining sufficiently small sensors to accommodate the large spatial variations encountered in non-planar loading; appropriate emplacement of sensors to obtain reliable in-situ data; and the difficulty in extending the sensor calibration from planar loading to non-planar loading conditions.[3]

To address the experimental needs indicated above, a short term exploratory research effort was undertaken to determine the feasibility of obtaining time-resolved, in-situ stress measurements in targets subjected to 2-D impact loading. The conceptual basis for the proposed stress measurements was provided by the experimental and analytic developments related to time-resolved examination of the ruby R-line shifts under plane shock wave loading.[4-9] This work, carried out under D.N.A. (now D.S.W.A.) sponsorship, has provided a detailed understanding of the piezo-spectroscopic response of

ruby R-lines to arbitrary dynamic loading. In our D.N.A. project,[10] concurrent with this A.R.O. project, we were examining the development of miniature optical sensors for use in plate impact experiments. While details of the extensive study on the ruby R-line shifts under shock loading may be seen elsewhere,[4-9] we summarize the following features of this work: the luminescene R-lines of ruby crystals undergo spectral shifts whose magnitude and direction of the shift (blue or red shift) depends on the stress amplitude and details of the loading conditions (hydrostatic, nonhydrostatic, compression or tension) and crystal orientation. Theoretical developments have been carried out that consistently model all available experimental data (hydrostatic, uniaxial stress, shock wave uniaxial strain compression and tension) and provide a determination of the spectral shift for any arbitrary deformation. Hence, these experimentally validated analytic developments provide a basis for relating the ruby R-line shifts to stresses encountered in 2-D and 3-D loading conditions.

The objective of this study was to determine if miniature ruby sensors could be used to measure in-situ stresses in targets subjected to rod impacts (2-D loading). Since this was a short term feasibility project, all of our effort was spent on experimental developments and obtaining experimental data for the loading conditions of interest.

The exploratory project was completed successfully and the remainder of the report summarizes the experimental developments and results. The findings described here make a good case for extending the present work to a longer term research effort to permit the use of miniature ruby gauges routinely for various Army applications involving rapid impulsive loading.

II. EXPERIMENTAL METHOD

A. Overall Configuration and Approach

The overall experimental configuration used in our work is shown in Figure 1. Because most aspects of the optical components and the recording instrumentation have been described elsewhere,[7-9] only a brief summary will be presented here. A 6.35 cm bore single stage, gas gun was used to accelerate projectiles to the desired velocities.[11] Cylindrical rods were mounted on the projectiles to provide the 2-D, axisymmetric loading conditions of interest.

Miniature ruby sensors (500 μm in diameter and 250 μm in thickness) were cut out from polished ruby discs (19 mm in diameter and 250 μm in thickness). The normal to the discs was oriented along the crystal c- or a-axis. Thus, all of the ruby chips we used had a well defined orientation. Each ruby chip was carefully examined to ensure that no cracks or blemishes were present and to ensure well polished surfaces and smooth edges. The ruby sensors were mounted at the tip of a fused silica optical fiber that had a 400 μm diameter fused silica core and 50 μm thick fused silica cladding. Prior to mounting the chip, the fiber was polished to ensure that the tip was flat. The measured epoxy bond thickness between the ruby sensor and the fiber was typically ≤5 μm.

Two points need to be emphasized about the above method. The final procedure that was developed was the culmination of a long effort in which we had to learn how to carry out each of the operations properly. Even now the sensor assembly is quite labor intensive and requires considerable care to ensure proper fabrication. We emphasize that only the miniature ruby disc, and not the fiber, acts as the stress sensor in our work. While the presence of the fiber can alter the dynamic stress distribution in and around the chip, its sole purpose is to transmit the of light to and from the ruby sensor. Since the completion of this work, we have considered the use of fibers and chips of both smaller and larger sizes.

In all of the experiments that we conducted, the target consisted of two parts: a thick cylindrical disc (typically, 35-38 mm in diameter and approximately 19 mm thick) with a thin cylindrical disc (typically 0.8 mm to 1.5 mm thick) of the same material as a front buffer. The choice of the buffer disc and the various sizes cited here was purely a matter of convenience. All of these can be altered as needed for a given application. In the thicker disc, a suitable hole (approximately 550 μm in diameter) was drilled perpendicular to the impact face to permit the ruby sensor to be embedded in the sample. The ruby gauge was epoxied in the target such that the sensor was flush with the impact side of the thicker disc. In one of the experiments, the ruby sensor face was coated with a metallic layer to enhance signal collection. The thin buffer disc was carefully bonded to the thicker disc using a very thin layer of epoxy.

In our experiments, either a CW argon ion laser operating at 514.5 nm or a flashlamp pumped dye laser (~ 3 μs pulse width) tuned to 514.5 nm was used to pump the ruby sensor. The use of a pulsed laser permits more efficient pumping to the ruby sensor.

This feature coupled with the reflective coating permits an improved signal to noise ratio. A single optical fiber, as shown in Figure 1, was used to deliver both the excitation light (514.5 nm) to the sensor and the resulting luminescence to the detection equipment.

At the detection system, the luminescence signal was separated from the reflected excitation light using a dichroic beam splitter. A double spectrograph was used to spectrally disperse the signal and a streak camera was used for temporal dispersion. The two dimensional streak image was intensified using an image intensifier and lens coupled to a CCD array. A multichannel analyzer was used to store the image and display it as intensity vs. wavelength vs. time.

The time resolution of the detection system was set to 100 ns-110 ns per spectrum for the measurements. This time resolution was chosen to permit a recording duration of >5 μs. The limiting time resolution of the gauge is determined by the sensor dimensions. For the sensors used in these measurements, the limiting resolution was approximately 50-60 ns, defined by the shock wave propagation time through the ruby longitudinally and laterally (the shock wave velocity in ruby is ~11 mm/μs at these stresses). We emphasize that considerable flexibility exists for both the time resolution and time duration, and different values can be obtained by a suitable choice of sensor sizes and detection equipment settings.

Each spectrum was calibrated to convert pixel number to wavelength. This was accomplished by recording the R-lines for five different spectrometer settings. The R-line peaks were fit to two Lorentzian functions and the peak position recorded. The five sets of pixel number and spectrometer setting were fit to a line which gave a dispersion of 0.6 Å/pixel at the CCD. The calibration was also verified using spectral calibration lamps of argon, neon, and helium.

B. Rod Impact Experiments

To determine the feasibility of obtaining high quality, time-resolved data for 2-D loading from the embedded ruby sensors described above, we chose to carry out rod impact experiments. The first part of our experimental work focused on developing a projectile design using rod impactors. We chose to mount rods (51 mm long and 12.7 mm in diameter), fabricated from OFHC copper, on our standard projectiles. This procedure was most convenient and provided the 2-D, axisymmetric loading of interest to us. The choice

of OFHC copper and the rod diameter permits a precise determination of the longitudinal stress while the sample is under uniaxial strain loading. No disturbance can arrive from the back of the copper rod during the recording time of interest. The release from the rod boundary results in non-planar or 2-D loading conditions in the target.

After the rod impactor design was successfully developed, a number of preliminary experiments were conducted to work out some of the experimental details. As shown in Figure 1, various equipment items are synchronized to the impact time by using trigger pins with appropriate heights. For the target samples, we chose to use 6061-T6 aluminum. This material has been extensively examined under shock loading and displays near ideal elastic-plastic response during compression.[12] The choice of OFHC impactor and 6061-T6 aluminum target allows an accurate determination of the uniaxial strain, impact stress (prior to the arrival of edge waves). Although 2-D calculations were outside the scope of the present feasibility project, the use of these materials can permit such calculations at a future date.

To examine the feasibility of the ruby measurements in a non-metallic target, we carried out one experiment with a Carrara marble target. This material undergoes elastic-plastic deformation and a phase change; its shock response has been carefully examined in a separate study by Aidun and Gupta.[13]

In all three of the experiments reported here, impactor velocities were chosen to be in the 0.55 mm/μs - 0.65 mm/μs range. This is a convenient range for one of our gas guns and results in impact stresses (uniaxial strain) ranging from 50 to 70 kbar. Choice of these parameters was somewhat arbitrary and was primarily a matter of convenience for this feasibility effort.

III. RESULTS AND DISCUSSION

Typical data from a ruby gauge embedded in 6061-T6 aluminum target impacted by an OFHC copper rod are shown in Figure 2. Spectra were recorded every 110 ns. The first seven spectra (prior to t = 0 in Figure 2) show the R-lines at ambient conditions (R_1 = 6943Å and R_2 = 6929Å) before the shock wave has reached the sensor. The spectrum at time, t = 0 is a superposition of the R-lines at ambient conditions and in the shocked state; this spectrum is convenient for establishing the arrival of the shock wave at the sensor.

There are six red shifted spectra following this superposed spectrum where the target is under uniaxial strain.

A lateral release wave due to the finite diameter of the copper rod results in a gradual blue shift of the red shifted R-lines toward the ambient positions. This blue shift lasts from $t = 0.8\ \mu s$ to $t = 1.8\ \mu s$. After $3\ \mu s$, the R-lines again undergo a red shift followed again by a blue shift. The temporal variations in the R-line shifts reflect the state of stress in the material due to the 2-D loading conditions. In all of our data, the intensities decreased during loading but returned to near ambient values upon release. While the exact cause for this change is not known, it is not of consequence to the present work since we are only interested in the spectral position of the R-lines. The time duration in Figure 2 was governed by the instrument settings. The $6\ \mu s$ recording time is shorter than the time for reflections to arrive from the back side of either the copper rod or the aluminum target. Hence, the temoral changes observed in Figure 2 are entirely due to lateral disturbances. The data in Figure 2 show clearly that a good determination of the in-situ response can be obtained for 2-D loading using miniature ruby sensors.

Each of the spectrum shown in Figure 2 was fitted to the sum of two Lorentzian functions and a constant background. The peak positions, intensity, and full width at half maximum (FWHM) were recorded for each spectrum. As stated earlier, only the peak position is of interest to the present work. Results from the three experiments are summarized in Table 1, and the R_1 and R_2 peak positions are plotted as a function of time in Figures 3-5, respectively.

The results in Figures 3 and 4 show that the rapid increase at $t = 0$ is preceded by a small change expected from the elastic precursor in 6061-T6 aluminum. The flat top peak region is followed by an unloading response due to lateral unloading. Subsequently, the signal follows the time-dependent changes due to lateral wave interactions in the sample.

The data from Carrara marble, shown in Figure 5, are more complicated because of the complex response expected for the shocked marble (presence of elastic-plastic deformation and a phase change).[13] Note, the presence of structure during the initial rise and unlike the aluminum, the response in marble shows significant hysteresis.

The data shown in Figures 3-5 have not been converted to stress histories because the procedures for inverting the measured R-line shifts to obtain stresses that would be present

in the samples, under 2-D loading, have not been worked out precisely. The difficulty is not in relating the R-line shifts to stresses in the ruby. Instead, the relationship between the stresses in the sensor and the stresses in the sample needs to be worked out. Such a calculation would require 2-D numerical calculations similar to those carried out recently for analyzing lateral piezoresistance gauges under shock wave loading.[14] Work is currently underway to permit inversion of the ruby R-line shifts to obtain sample stresses.

Although the data in Figures 3-5 have not been inverted, some comments about the R-line shifts from our earlier work under plane wave loading are in order.[4-9] The R_2 line shift is related directly to the mean stress in the sensor. The R_1- R_2 splitting is a measure of the stress deviators in the sensor. Finally, we point out that the "forward problem" involving the calculation of the R-line shifts for an assumed sample response can be carried out using 2-D numerical simulations. Thus, data similar to that reported here can be used to evaluate numerical simulations of 2-D dynamic loading conditions.

IV. CONCLUDING REMARKS

The experimental developments reported here show that miniature optical stress sensors can be used to determine the target response in 2-D loading situations arising due to projectile impacts. Given the importance of obtaining in-situ, stress histories under non-planar or 2-D dynamic loading conditions, the results reported here represent a major step in resolving a problem of long standing. However, the present work constitutes a start and further work needs to be carried out before the developments reported here can be used routinely in Army applications involving projectile impacts. Many more experiments need to be carried out to establish the experimental limits including the stress bounds.

More importantly, a carefully analytic/numerical effort needs to be undertaken to develop accurate procedures to invert the sensor output in a meaningful manner. Unlike plane wave loading, analysis of any sensor response under 2-D loading is not straightforward. Numerical solutions need to be carried out to develop an in depth understanding of the gauge response and to establish procedures to analyze the gauge output.

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TABLE 1. Summary of Rod Impact Experiments.

Experiment No.	Impactor-Target Material	Impact Velocity (mm/μs)	Peak Matrix Stress[a] (kbar)	Peak R-Line Shift		Signal Duration (μs)
				R_1-line (Å)	R_2-line (Å)	
1	Cu-Al	0.629	70.5	25.6±1	25.2±1	6.0
2	Cu-Al	0.584	65.1	23.5±0.4	23.2±0.4	6.25
3	Cu-Carrara Marble	0.566	50	20.4±1	19.4	5.5

[a]Calculated peak longitudinal stress corresponding to uniaxial strain loading.

[b]Recording time as determined by the detector setting.

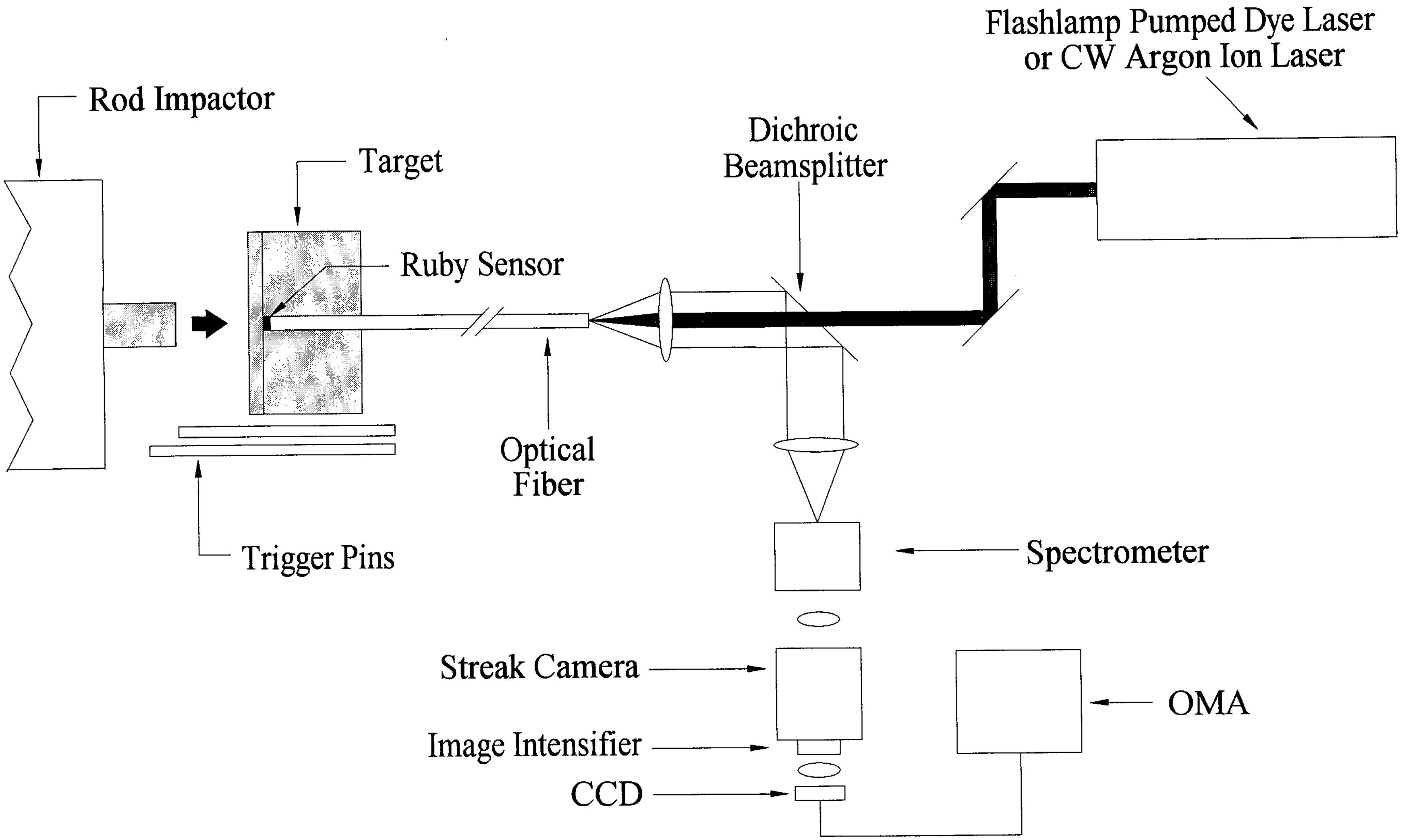

Figure 1: Experimental configuration for obtaining time resolved spectra from a ruby gauge embedded in a target.

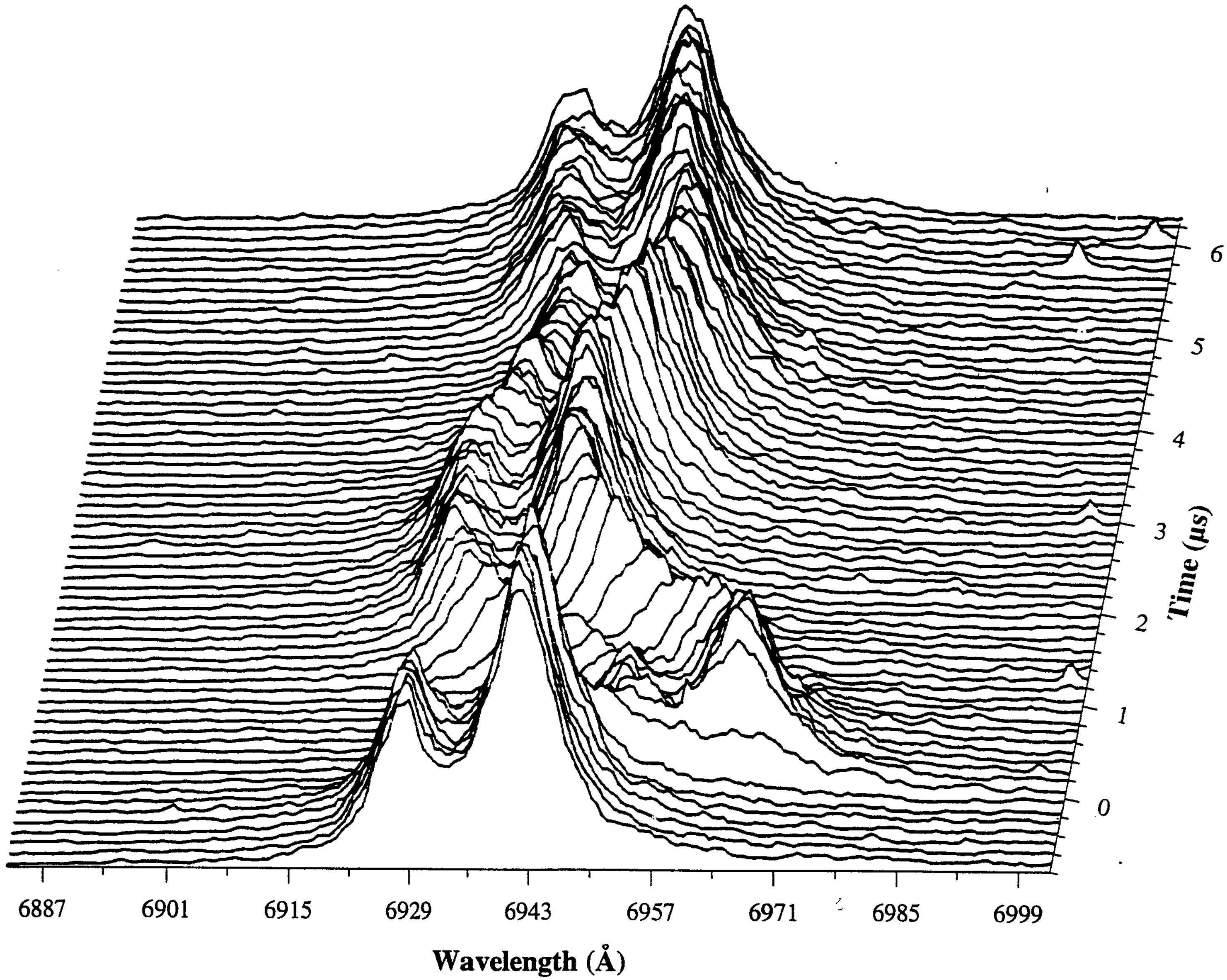

Figure 2: Time resolved spectra from a ruby sensor embedded in 6061 T6 aluminum. Spectra prior to t = 0 show the R-lines at ambient conditions. Upon shock wave arrival at the sensor, the R-lines red shift. After approximately 0.8 μs the R-lines gradually blue shift due to lateral release waves.

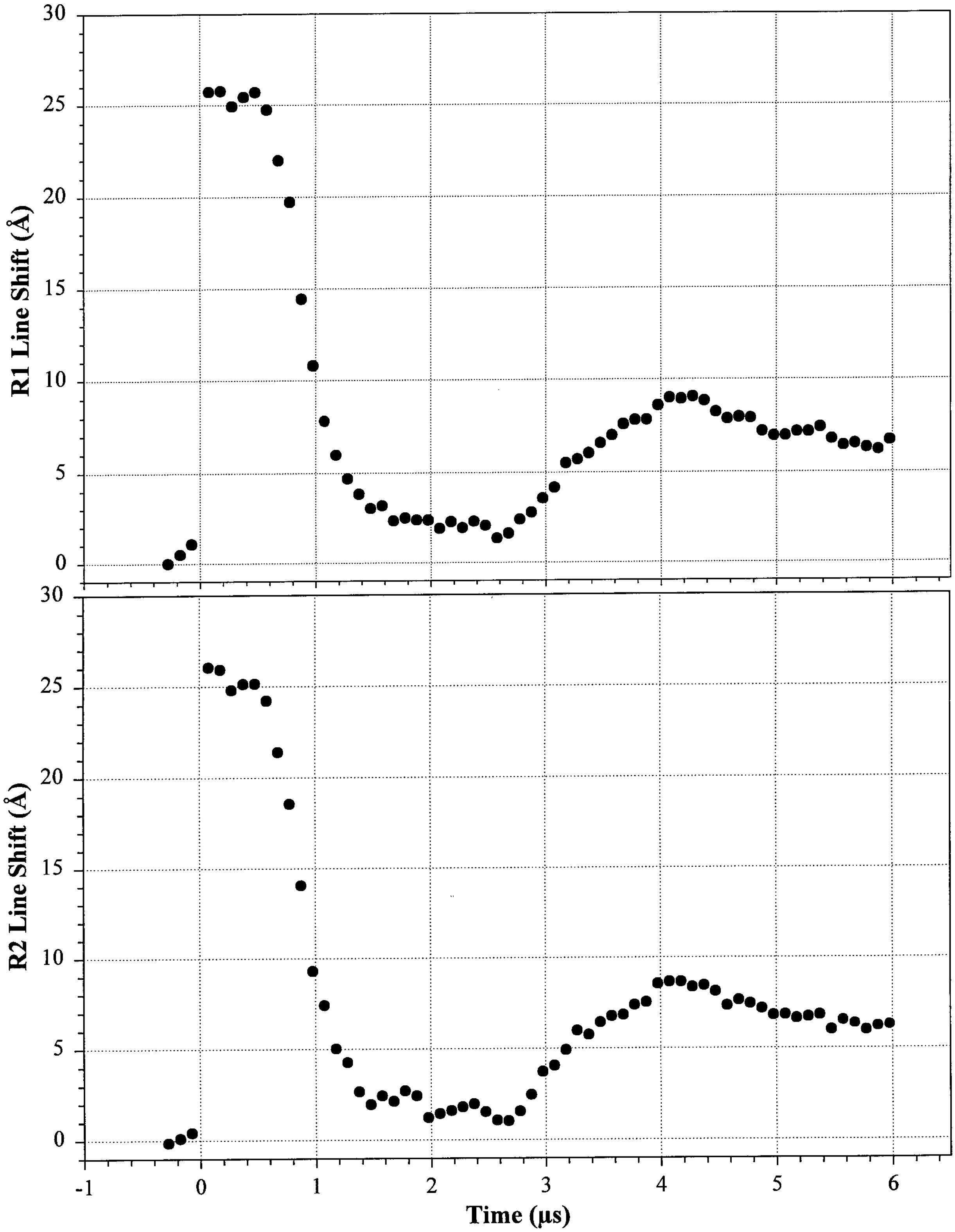

Figure 3: The R1 and R2 line shifts with respect to the ambient R-line positions for Experiment 1. The measurement was limited in time by the record duration not by failure of the gauge.

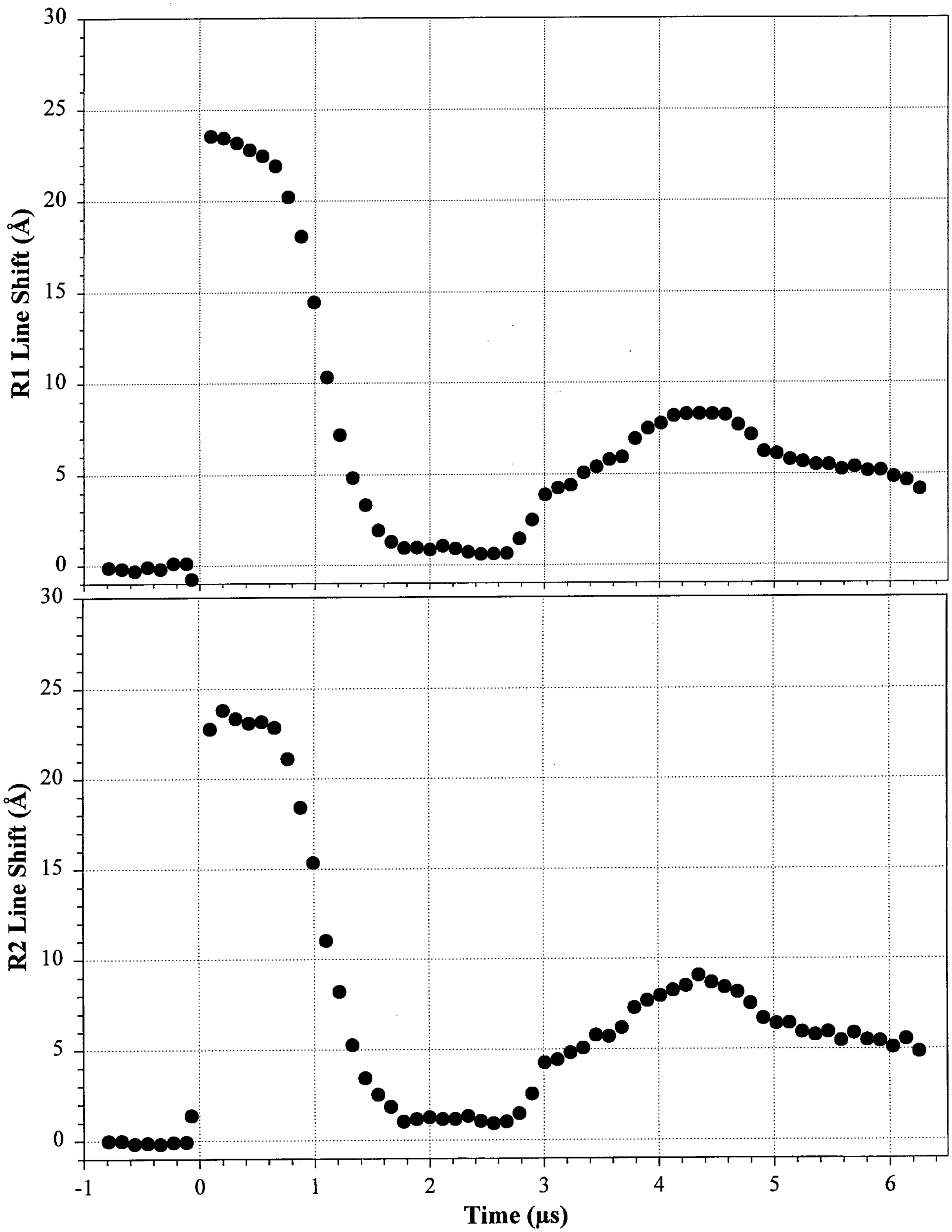

Figure 4: The R1 and R2 line shifts with respect to the ambient R-line positions for Experiment 2. The measurement was limited in time by the record duration not by failure of the gauge.

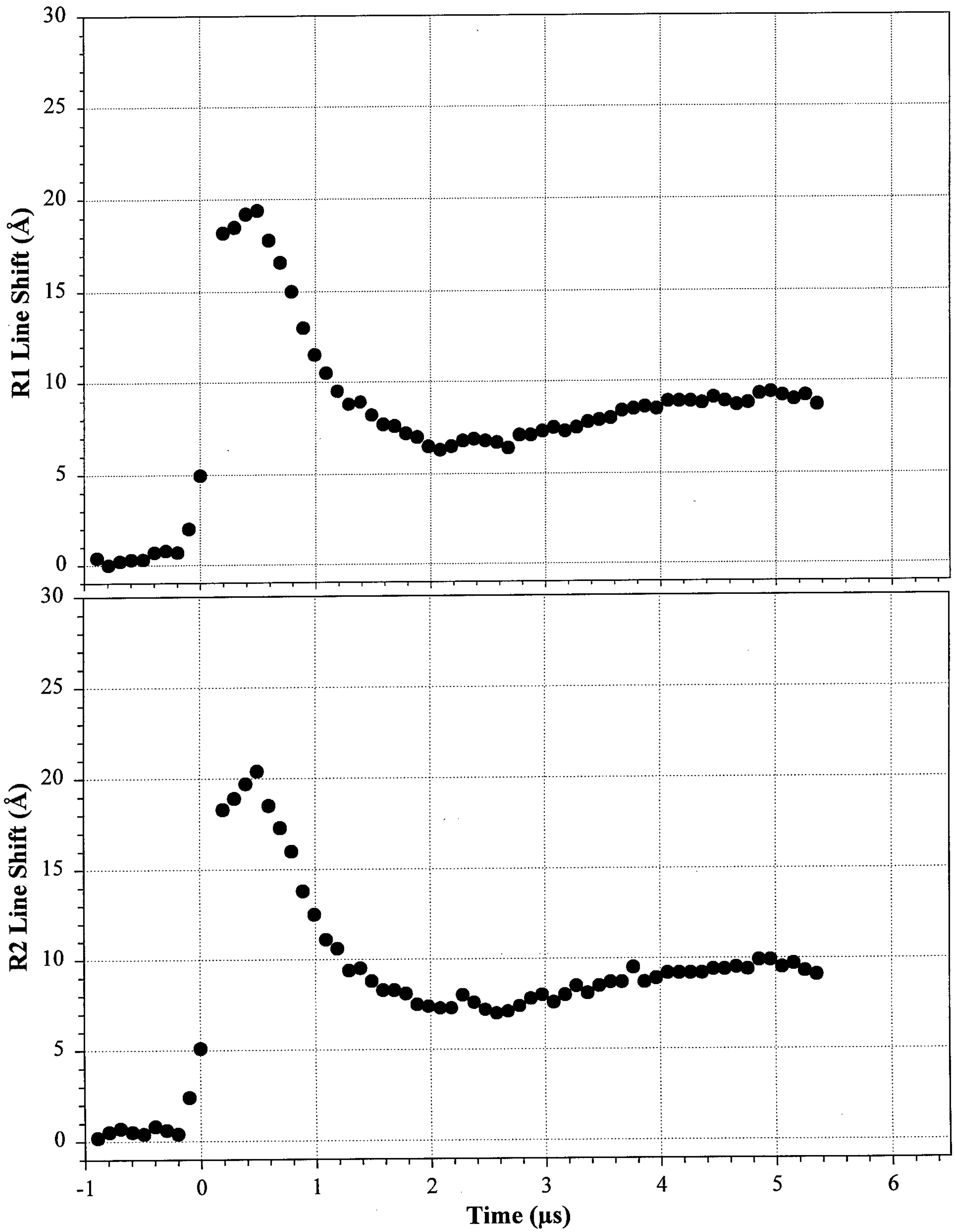

Figure 5: The R1 and R2 line shifts with respect to the ambient R-line positions for Experiment 3. The measurement was limited in time by the record duration not by failure of the gauge.